Low energy effects of Higgs induced leptoquark-diquark mixing

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Abstract

In low energy phenomenology to avoid the strong constraints of proton decay it is usually assumed that light ($\approx$ 250 Gev) leptoquarks couple only to quark-lepton pairs and light diquarks couple only to quark pairs. In this work we show that the SM Higgs boson could induce a mixing between leptoquarks and diquarks through trilinear interaction terms which reintroduces the troublesome couplings and lead to proton decay. The bound on the unknown parameters of this scenario that arise from proton life time has also been derived.

Leptoquarks (LQ) [1] and diquarks (DQ) [2, 3] are colored scalar or vector particles that carry baryon numbers of $\pm\frac{1}{3}$ and $\pm\frac{2}{3}$ respectively. They occur naturally in many extensions of the standard model (SM) e.g. superstring inspired grand unified models based on $E(6)$ [3], technicolor models [2] and composite models [1] of quarks and leptons. If LQs and DQs couple both to quark-lepton pairs and quark pairs then they lead to too rapid proton decay. To be consistent with the proton life time such LQs and DQs must have a mass of the order of $10^{12} - 10^{15}$ Gev. To avoid this strong constraint and to make them relevant for low energy phenomenology below 1 Tev it is usually assumed that LQs couple to quark-lepton pairs but not to quark pairs and DQs couple to quark pairs but not to quark-lepton pairs. However in the presence of the SM higgs doublet ϕ the low energy effective Lagrangian will also contain a trilinear Higgs-LQ-DQ interaction term. After EW symmetry breaking (EWSB) this interaction term will induce a mixing between the LQ and the DQ which reintroduces the troublesome Yukawa couplings for LQ and DQ. If the physical LQ and DQ do not have the same mass then they lead to proton decay. In this report we give a few concrete examples of Higgs-LQ-DQ interaction term and the mixing between the LQ and DQ that takes place after EWSB. For one particular case we have also calculated the mixing angle in terms of the dimensional coupling that measures the strength of the Higgs-LQ-DQ interaction term. Finally we have estimated the proton decay rate in terms of the unknown parameters of our scenario and have derived a bound on their product from the bound on the proton life time.

Consider the SM to be extended by a light (≈ 250 Gev) chiral leptoquark D and a light chiral diquark S with the following assignments under $SU(3)_c \times SU(2)_l \times U(1)_y$: $D \sim (3^*, 2, -\frac{1}{6})$ and $S \sim (3^*, 1, \frac{1}{3})$. The low energy effective Lagrangian of this extended scenario will contain besides the SM Lagranigian all possible renormalizable and gauge invariant interaction terms between D, S and the SM fields. Of particular importance for this work are the Yukawa like couplings of D and S to the SM fermions given by the following Lagrangian

$$\begin{aligned} L_y &= g_R \bar{l}_L d_R D + g' \epsilon_{ijk} \bar{d}_{Ri} u^c_{Rj} S_k + h.c. \\ &= g_R(\bar{\nu}_L D_1 + \bar{e}_L D_2) d_R + g'_R \epsilon_{ijk} \bar{d}_{Ri} u^c_{Rj} S_k + h.c. \end{aligned} \tag{1}$$

Here D_1 and D_2 are the isospin up and down components of D. i, j, k are the color indices. Note first that the leptoquark D couples only to quark-lepton pair and the diquark S couples only to quark pair which is required so that they do not lead to proton decay. Second both interaction terms are invariant under the SM gauge group $SU(3)_c \times SU(2)_l \times U(1)_y$. Finally the couplings of D and S are both chiral in nature i.e. they couple to quark fields of a particular chirality only. The Yukawa Lagrangian L_y also implies that D and S should carry baryon numbers of $-\frac{1}{3}$ and $\frac{2}{3}$ respectively so that L_y conserves baryon number. This kind of structure of the Yukawa couplings could arise depending on the gauge symmetry of the high energy theory and its chiral matter representstion. Besides the Yukawa couplings the low energy Lagrangian for describing physics much below the compositeness scale or grand unified scale Λ must also contain all possible renormalizable and gauge invariant interaction terms between ϕ, D and S. In principle such interaction terms cannot be neglected. They could arise from the scalar potential of the high energy theory after the gauge symmetry of the high energy theory breaks down into $SU(3)_c \times SU(2)_l \times U(1)_y$. The gauge invariant trilinear interaction term between ϕ, D and S is given by the Lagrangian

$$L_s = k_1 (D^+ \phi_c) S + h.c. = k_1 \frac{v+h}{\sqrt{2}} D_1^+ S + h.c. \tag{2}$$

Here ϕ_c is the charge conjuated Higgs doublet that gives mass to the up quarks in SM. The unknown mixing parameter k_1 carries the dimension of mass. After EW symmetry breaking this interaction term will lead to mixing between D_1 and S. Note that D_1 and S carries the same charge and color assignments which is necessary so that they could mix after EWSB. The above higgs-LQ-DQ interaction term violates both baryon number and lepton number by one unit ($\delta B = -\delta L = 1$). Here we are implicitly assuming that the breaking of baryon number symmetry is first communicated to the scalar sector of the high energy theory which in turn communicates it to other sectors e.g the Yukawa sector. Recall that in the SM baryon number conservation is realized as an accidental global symmetry [4]. By that we mean that given the particle content and the gauge group $SU(3)_c \times SU(2)_l \times U(1)_y$ of the SM it is not possible to write a renormalizable

and gauge invariant interaction term that violates baryon number. No adhoc global symmetry is required to explain the near abscence of proton decay. However as we have seen above that if we keep the gauge group the same but allow additional particles like color triplet scalars then it is possible to write down a renormalizable and gauge invariant interaction term that violates baryon number.

We shall now show that the mixing between D_1 and S induced by ϕ can lead to proton decay in the "ν + any channel" where any refers to a positively charged non-strange meson. Consider the full scalar potential involving D and S

$$\begin{aligned} V(D,S) &= \mu_1^2 D^+ D + \mu_2^2 S^+ S + \lambda_1 (D^+ D)^2 + \lambda_2 (S^+ S)^2 \\ &+ \lambda_1' (D^+ D)(\phi^+ \phi) + \lambda_2' (S^+ S)(\phi^+ \phi) + (k_1 D^+ \phi_c S + h.c.) \end{aligned} \tag{3}$$

The quartic scalar interactions are not relevant to our present work. μ_1^2 and μ_2^2 are the mass parameters associated with the gauge eigenstates D and S. After EWSB the trilinear interaction term between ϕ, D and S induces a mixing between D_1 and S. It can be shown that the mass eigenstates are given by $D_1' = D_1 \cos\theta - S \sin\theta$ and $S' = D_1 \sin\theta + S \cos\theta$ where $\sin\theta = \frac{\frac{k_1 v}{\epsilon}}{\sqrt{1+\frac{k_1^2 v^2}{\epsilon^2}}}$, $\epsilon = \mu_1^2 - \mu_2^2$ and $v = \langle\phi\rangle$ =250 Gev. In deriving this expression for $\sin\theta$ we have assumed that $\frac{k_1 v}{\epsilon} \ll 1$. The corresponding mass eigenvalues are given by $M_D^2 = \mu_1^2 + \frac{k_1^2 v^2}{2\epsilon}$ and $M_S^2 = \mu_2^2 - \frac{k_1^2 v^2}{2\epsilon}$.

The Yukawa couplings of the LQ and the DQ written in terms of mass eigenstates are given by

$$\begin{aligned} L_y &= g_R [\bar{\nu}_L (D_1' \cos\theta + S' \sin\theta + \bar{e}_L D_2] d_R \\ &+ \epsilon_{ijk} g_R' \bar{d}_{Ri} u_{Rj}^c [S_k' \cos\theta - D_{1k}' \sin\theta + h.c.] \end{aligned} \tag{4}$$

. The above Yukawa Lagrangian does lead to proton decay in the "ν + any" channel via the exchange of D and S particles. The effective four fermion Lagrangian for this decay is given by

$$L_{eff} = g_R g_R' \sin\theta \cos\theta \epsilon_{ijk} (\bar{\nu}_L d_{Rk})(\bar{u}_{Rj}^c d_{Ri}) (\frac{1}{M_S^2} - \frac{1}{M_D^2}) + h.c. \tag{5}$$

This is the effective Lagrangian at a scale $M^2 = M_D^2 \approx M_S^2 \approx (250Gev)^2$. In order to use it for proton decay it has to be renormalized down to a scale $\mu^2 = (1Gev)^2$ under the unbroken QCD and EM interactions. The EM corrections are small because the coupling itself is small. The QCD corrections are not that large either because $\ln\frac{M^2}{\mu^2}$ is not large in our case. It can be shown that the proton decay rate arising from the above effective Lagrangian is given by

$$\Gamma(p \to \nu_e + any) \approx \frac{1}{17\pi^2 R^3} G_{eff}^2 m_q^2 A^2 (\frac{M}{\mu}) \tag{5}$$

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Here $A(\frac{M}{\mu})$ includes the effects of renormalization group evolution from M to μ. We shall assume it to be of order one. $R = \frac{3}{4}$ fm, $m_q \approx \frac{1}{3}$ Gev and $G_{eff} = \frac{1}{2\sqrt{2} g_R} g_R' \sin\theta \cos\theta (\frac{1}{M_S^2} - \frac{1}{M_D^2})$. The present lower bound on $\tau(p \to \nu + any)$ is $25{\times}10^{30}$ yr [5]. For M_S = 200 Gev and M_D = 300 Gev [6] the product combination $g_R g_R' \sin\theta \cos\theta$ must be less than 3×10^{-26} in order to be consistent with proton stability. If we assume that the Yukawa couplings g_R and g_R' are of the order of .1 and that $\sin\theta \ll 1$ we then get the upper bound $k_1 < 6 \times 10^{-13}$ ev. The extreme smallness of this dimensionful parameter compared to other mass scales that appear in our extended scenario implies that the corresponding interaction term must be prevented from occuring in the low energy Lagrangian by means of some new symmetry (gauge or global) that remains unbroken in the low energy effective theory. Note that the mixing between D and S and hence proton decay occurs only for specific $SU(3)_c \times SU(2)_l \times U(1)_y$ assignments of the LQ and the DQ. Unless these assignments are achieved there is no mixing between D and S and no contribution to proton decay.

Having shown that higgs induced mixing between the doublet leptoquark D and the singlet diquark S does lead to proton decay we shall now present another concrete scenario where the same phenomenon also takes place. An EW triplet diquark T_{ak} (a is the $SU(2)_l$ index and k the color index) can also mix with the

doublet leptoquark D and contribute to both proton decay and neutron decay. Let the $SU(3)_c \times SU(2)_l \times U(1)_y$ assignments of T_{ak} be given by (3, 3, $-\frac{1}{3}$). The triplet diquark T_{ak} can couple to LH quark pair according to the following Lagrangian:

$$\begin{aligned} L'_y &= g''_R \epsilon_{ijk} \bar{q}^c_{Li} \tau_a i \tau_2 T_{ak} + h.c. \\ &= g''_R \epsilon_{ijk} [-\sqrt{2} \bar{u}^c_{Li} u_{Lj} T_{-k} + \sqrt{2} \bar{d}^c_{Li} d_{Lj} T_{+k} + (\bar{u}^c_{Li} d_{Lj} + \bar{d}^c_{Li} u_{Lj}) T_{0k}] \end{aligned} \tag{6}$$

where $T_{+k} = \frac{T_{1k}+iT_{2k}}{\sqrt{2}}$, $T_{-k} = \frac{T_{1k}-iT_{2k}}{\sqrt{2}}$ and $T_{0k} = T_{3k}$. T_{+k} and T_{-k} carry electromagnetic charges of $\frac{2}{3}$ and $-\frac{4}{3}$ units respectively. Note that T_{-k} is not the antiparticle of T_{+k} since they carry different electromagnetic charges. The gauge invariant Higgs-LQ-DQ interaction term in this case will be given by

$$\begin{aligned} L'_s &= k_2 (D^+ \tau_a \phi_c) T^*_a + h.c. \\ &= k_2 \frac{v+h}{\sqrt{2}} [D^+_2 T^*_+ + D^+_1 T^*_0 + h.c.] \end{aligned} \tag{7}$$

The mixing between D_1 and T^*_0leads to $p \to \pi^+ \nu$ and the mixing between D_2 and T^*_+ leads to $n \to \pi^+ e^-$ both of which violate baryon number.

The low energy effective Lagrangian will also contain trilinear Higgs-LQ-LQ and Higgs-DQ-DQ interaction terms. Afetr EWSB these terms give rise to mixing between different multiplets of LQ and DQ. Such interaction terms do not violate baryon number but they could violate lepton number. Of particular importance is the Higgs-LQ-LQ ineraction for a pair of chiral leptoquarks belonging to different weak SU(2) multiplets. The mixing between two different LQ multiplets will give rise to helicity unsuppressed contribution to $\pi^- \to e^- \bar{\nu}_e$ The helicity suppressed SM contribution to $\pi^- \to e^- \bar{\nu}_e$ is in excellent agreement with the experimental data. Therefore any helicity unsuppressed contribution arising from new physics must be strongly constrained. This leads to stringent bounds on the mixing parameter between the two LQ multiplets. The mixing between different LQ multiplets can also lead to majorana mass matrix for neutrinos. A complete discussion of these topics can be found in Ref. [7] and will not be taken up here.

To conclude in this report we have shown that the usual assumption of low energy phenomenology that LQ's couple only to q-l pairs and DQ's couple only to quark pairs is not sufficient to stabilize the proton. The Higgs-LQ-DQ interaction term that occurs in the low energy effective Lagrangian induces a mixing between the LQ and DQ after EWSB. This mixing reintroduces the troublesome couplings for the LQ and the DQ and lead to proton decay. We have found that in order to be consistent with the bound on proton life time the parameter k_1 must be extremely small ($k_1 < 6 \times 10^{-13}$ ev) if the LQ and DQ masses are in the few hundred Gev range and their Yukawa couplings are of the order of .1. Such an extremely small mass parameter is rather unnatural. The problem can be resloved by means of some new symmetry that remains unbroken in the low energy theory and prevents the Higgs-LQ-DQ interaction term from occuring in the effective Lagrangian.

References

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